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Demonstration of an oxyfuel combustion system

D W Sturgeon[a]*, E D Cameron[a], F D Fitzgerald[a]

[a]*Doosan babcock Energy Limited, Porterfield Road, Renfrew, PA4 8DJ, UK*

Abstract

Doosan Babcock is aiming to develop a competitive oxyfuel firing technology suitable for full plant application post 2010, and is taking a phased approach to the development and demonstration of oxyfuel technology. Doosan Babcock is leading a number of UK Government supported collaborative projects that are developing oxyfuel combustion technology. The "Fundamentals and Underpinning Technologies" project aims to develop a competitive oxyfuel firing process based on the integration of well proven and innovative power plant design components, addressing critical technology gaps such as combustion fundamentals, furnace design and operation, novel flue gas purification technologies and generic process issues. The "Demonstration of an Oxyfuel Combustion System" project aims to demonstrate an oxyfuel combustion system of a type and size ($40MW_t$) applicable to new build and retrofit advanced supercritical boiler plant. These two projects are discussed in the paper and preliminary results from pilot-scale testing undertaken in the first of these are presented.

Keywords: carbon capture and storage; oxyfuel combustion; OxyCoal™

1. Introduction

To achieve the global target reduction in CO_2 emissions of some 60% by 2050 [1], carbon dioxide capture and permanent underground storage (CCS) will be necessary. Carbon abated clean coal technologies (CATs) will be required for retrofit to existing power plant and installation on new build power plant.

Doosan Babcock Energy Limited, a multi-specialist energy services company, has taken a proactive approach to developing CATs, leading and supporting techno-economic studies on both Track 1 and Track 2 approaches of the UK DTI's Carbon Abatement Technology Strategy [1]. The Track 1 approaches are available now and reduce CO_2 emissions per unit of electricity generated by means of improved cycle efficiency and biomass co-firing (carbon neutral). The Track 2 approach, CCS, achieves much larger reductions, up to 95%, by means of oxyfuel combustion, post-combustion capture or integrated gasification combined cycle (IGCC) technologies.

Initially, studies were undertaken at a high level, i.e. technical and economic feasibility. Two notable such studies were undertaken as part of the IEA Greenhouse Gas (IEA GHG) R&D programme and focused on new build power plant, with post-combustion capture of CO_2 [2] and oxy-combustion processes for CO_2 capture [3]. The

* Corresponding author. Tel.: +44(0)141 885 3513; fax: +44(0)141 885 3860.
E-mail address: dsturgeon@doosanbabcock.com.

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technical and economic aspects were investigated in detail, considering integration of the CATs, determining relative benefits of alternative approaches and reviewing the applicability of optimum solutions. Projects were also completed to evaluate and optimize how CAT retrofits can be accomplished on the UK fleet of coal-fired power plants [4], to demonstrate the potential application of advanced supercritical (ASC) pulverized fuel (PF) boiler / turbine technology and CO_2 capture capabilities to the Canadian power generation market [5], and to develop new build designs of oxyfuel greenfield pulverized fuel (PF), bituminous and lignite, coal-fired power plants (Enhanced Capture of CO_2 (ENCAP) oxyfuel combustion sub-project) [6]. An overview of Doosan Babcock's approach to the implementation of oxyfuel technology is presented in [7]. The studies concluded that post-combustion capture and oxyfuel combustion are technically feasible and represent competitive options for CO_2 capture that could be applied to both new build and existing plant as retrofit. However, research, development and demonstration of the technologies are required in the short-term to gain operational experience and provide confidence at pilot-scale and then full-scale, and in the long-term to improve performance and efficiency loss, making the CATs more attractive economically.

Doosan Babcock has been investigating oxyfuel technology as a means to achieve efficient near zero emission power generation since the early 1990s.

Oxyfuel firing, the combustion of fuel in a medium comprising injected oxygen plus recycled flue gas, offers a means of generating carbon dioxide rich flue gas requiring minimal treatment prior to sequestration or beneficial application. The oxyfuel combustion process differs from air firing in a number of ways that lead to uncertainties in the development of design methods.

Doosan Babcock is aiming to develop a competitive oxyfuel firing technology suitable for full plant application post 2010, and is taking a phased approach to the development and demonstration of oxyfuel technology; Fundamentals and Underpinning Technologies (2007-2008), Demonstration of an Oxyfuel Combustion System (2007-2009) and Reference Designs (2009-2010).

Doosan Babcock is leading a number of UK Government supported collaborative projects that are developing oxyfuel combustion technology, including:

- Investigation of oxyfuel combustion fundamentals and underpinning technologies
- Demonstration of a full-scale ($40MW_t$) oxyfuel burner

These two projects are discussed here.

2. Fundamentals and underpinning technologies

The "Fundamentals and Underpinning Technologies" project is seen as the first step in providing confidence to proceed to full-scale demonstration of oxyfuel firing technology.

The project participants in the £2.2M UK Department for Business Enterprise & Regulatory Reform (BERR) Technology Programme collaborative project comprise: Doosan Babcock Energy Limited (Lead), Air Products plc, E.ON UK plc, RWE npower plc, BP Alternative Energy International Limited, University of Nottingham and Imperial College London. Scottish and Southern Energy plc, ScottishPower Energy Wholesale, EDF Energy plc, Drax Power Limited and DONG Energy A/S are sponsor participants.

The project aims to develop a competitive oxyfuel firing process based on the integration of well proven and innovative power plant design components, addressing critical technology gaps such as combustion fundamentals, furnace design and operation (slagging, fouling and corrosion), novel flue gas purification technologies, and generic process issues (safety, reliability, availability, maintainability and operability). The technical approach emphasizes the use of small-scale testing, supported by a series of modeling and engineering design studies, to generate the practical understanding and experience required to mitigate or eliminate technical risks and uncertainties.

The objectives of the study of combustion fundamentals are to investigate coal ignition, devolatilization, char burnout, char intrinsic reactivity and nitrogen partitioning behavior of six UK and world-traded coals under oxyfuel firing conditions.

Imperial College, London, investigated coal ignition behavior at the National Institute for Occupational Safety and Health (NIOSH) Pittsburgh Research Laboratory, PA, USA, completing explosion bomb characterization tests for each of the six UK and world-traded coals under oxyfuel firing conditions.

The University of Nottingham investigated devolatilization, char burnout, char intrinsic reactivity and nitrogen partitioning behavior under oxyfuel firing conditions in a drop-tube furnace (DTF), and to-date has tested five of the six UK and world-traded coals.

Doosan Babcock is analyzing the DTF characterization tests data and building computational fluid dynamic (CFD) models to establish corresponding coal devolatilization and char burnout kinetic parameters. This will lead to development of a CFD modeling predictive capability under oxyfuel firing conditions for application in simulations of a single oxyfuel burner and an oxyfuel-fired power station furnace.

The work on furnace design and operation comprised characterization of the oxyfuel process and its key impacts on utility plant operation and performance. Pilot-scale testing of one UK and one world-traded coal under oxyfuel firing conditions was carried out by E.ON UK at their $1MW_t$ combustion test facility (CTF), with the parametric testing of the oxyfuel combustion process building operational experience. The impacts on slagging, fouling and corrosion were investigated with test deposit samples characterized using a computer controlled scanning electron microscope (CCSEM) by Imperial College, London. In addition, laboratory-scale corrosion testing has been completed by Doosan Babcock to evaluate the suitability of candidate materials for boiler final superheater and reheater sections under simulated oxyfuel flue gas.

A laboratory-scale flue gas purification system was developed and tested, using synthetic oxyfuel flue gas, by Imperial College, London. The apparatus was relocated to Doosan Babcock's $160kW_t$ NO_x Reduction Test Facility (NRTF), where this novel CO_2 clean-up process was tested using real oxyfuel flue gas. Parametric testing of the oxyfuel combustion process was also undertaken on the NRTF.

The generic process issues activities investigated the key issues associated with an oxyfuel installation on a large utility plant, focusing on a safety assessment and a reliability, availability, maintainability and operability (RAMO) assessment. A front end-engineering design (FEED) study for the oxyfuel conversion of Doosan Babcock's $90MW_t$ Multi-Fuel Burner Test Facility (MBTF) was also completed. The FEED study included a preliminary hazard and operability (HAZOP) study, which identified key concerns and mitigating actions.

3. NO_x reduction test facility

The $160kW_t$ NO_x Reduction Test Facility (NRTF), located at Doosan Babcock's Research and Development (R&D) Centre in Renfrew, Scotland, was originally designed for the investigation of primary in-furnace NO_x control technologies. It has since been modified to allow development of selective catalytic reduction (SCR) and selective non-catalytic reduction (SNCR) post-combustion NO_x reduction processes, and for the oxyfuel combustion process. A schematic diagram of the NRTF is shown in Figure 1. The furnace is 5.0 m long and 0.5 m in diameter, arranged vertically. The burner, a residence time scaled down version of a $42MW_t$ commercial low NO_x axial swirl burner, is located at the top of the furnace and fires vertically downwards. The furnace is refractory lined and a water jacket removes heat to a forced draught air-cooled heat exchanger. Pulverized coal is supplied pre-ground and is fed at a controlled rate by a loss-in-weight feeder. For air firing, primary air is supplied by a blower and is pre-heated electrically to give a delivery temperature of around 60 to 70°C at the burner. Secondary air is supplied by a forced draught fan and is heated electrically to around 230°C. Two reactors are installed in series downstream of the furnace to allow the investigation of post-combustion NO_x control technologies. The hot flue gases leave the furnace and pass via the two reactor sections to an air cooled heat exchanger. The heat exchanger is positioned upstream of the SCR reactor to control the SCR inlet flue gas temperature within the catalyst's optimum operating temperature range. The cooler reduces the flue gas temperature from nominally 900°C to nominally 400°C. Ammonia can be injected into the flue gas via a NH_3 injection system just upstream of the SCR. On leaving the SCR, the flue gas enters a second air-cooled heat exchanger. This heat exchanger is positioned upstream of the electrostatic precipitator (ESP) to reduce its inlet flue gas temperature to nominally 150°C. Following fly ash removal by the ESP the flue gas is exhausted to atmosphere via an induced draught fan.

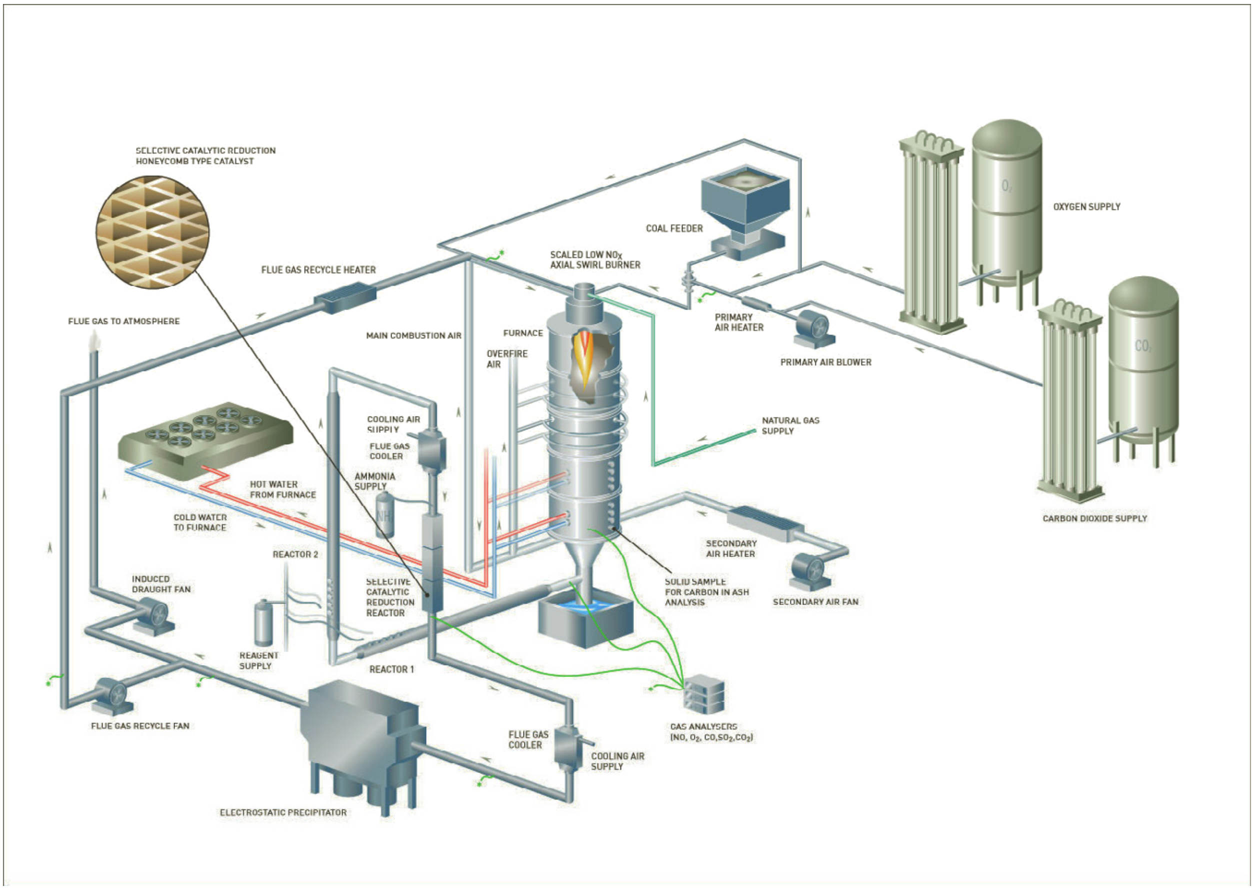

Figure 1: NO_x reduction test facility

For oxyfuel firing, primary air is replaced with transport CO_2 supplied from a liquid storage tank and is vaporized on demand. Secondary air is replaced with flue gas recycled from the ESP outlet. Oxygen is injected into both the transport CO_2 (primary) and flue gas recycle (secondary) streams upstream of the coal injection point and windbox respectively. Oxygen is stored as liquid and is vaporized on demand.

4. Experimental results for 160kW$_t$ NO_x reduction test facility

Pilot-scale testing of a world-traded coal under air and oxyfuel firing conditions was undertaken. Oxyfuel flue gas was supplied to a lab-scale sour compression rig designed and built by Imperial College, based on part of the process of Air Products plc's novel flue gas clean-up technology for the purification of oxyfuel derived CO_2 [8,9]. Simultaneous parametric testing of the oxyfuel combustion process was carried out, investigating the effect of burner stoichiometric ratio, flue gas recycle (FGR) ratio, primary transport gas O_2 oxygen content, and selective catalytic reduction (SCR).

Process conditions such as flows, temperatures and pressures, flue gas analysis for NO, O_2, CO, SO_2, CO_2, SO_3, NH_3, and Hg, and laboratory analysis for carbon in ash (CIA), Hg in ash were measured. Preliminary results are presented.

Furnace exit CO_2 concentrations achieved during oxyfuel firing were in excess of 75%v/v dry following air ingress minimization, compared to conventional air firing, typically 15%v/v dry. This demonstrated that the oxyfuel combustion process produced a CO_2 rich flue gas over a reasonable operational envelope that could undergo inerts removal and purification, prior to compression and sequestration.

4.1. Effect of burner stoichiometric ratio

The effect of burner stoichiometric ratio on furnace exit NO is presented in Figure 2. On a volumetric basis (vppm) air firing and oxyfuel firing furnace exit NO concentrations are comparable. However, on a heat input basis (mg/MJ) oxyfuel firing furnace exit NO is reduced by approximately 50% compared to air firing furnace exit NO. It is postulated that this reduction is due to conversion of recycled NO to HCN by reaction with hydrocarbon radicals in the flame. The HCN formed will react to form N_2 under oxygen lean, fuel rich conditions, or NO under fuel lean, oxygen rich conditions. In effect the recycled NO is reduced by the process of reburning, this NO_x reduction technology having been demonstrated at ENEL's 320MW$_e$ Vado Ligure power station [10].

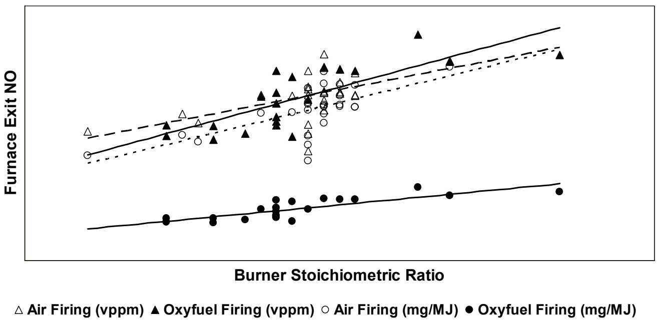

Figure 2: Effect of burner stoichiometric ratio on furnace exit NO

The effect of burner stoichiometric ratio on furnace exit SO_2 is presented in Figure 3. On a volumetric basis (vppm) oxyfuel firing furnace exit SO_2 concentration is approximately double compared to air. However, on a heat input basis (mg/MJ) oxyfuel firing furnace exit SO_2 is reduced by approximately 25% compared to air firing. Preliminary analysis of a sulfur balance has shown that this reduction is due to the higher concentration of oxyfuel firing furnace exit SO_2 leading to increased SO_2 retention by the fly ash, i.e. the proportion of SO_2 in the ash phase is higher during oxyfuel firing compared to air firing, and hence, the proportion of SO_2 in the gas phase is lower during oxyfuel firing compared to air firing.

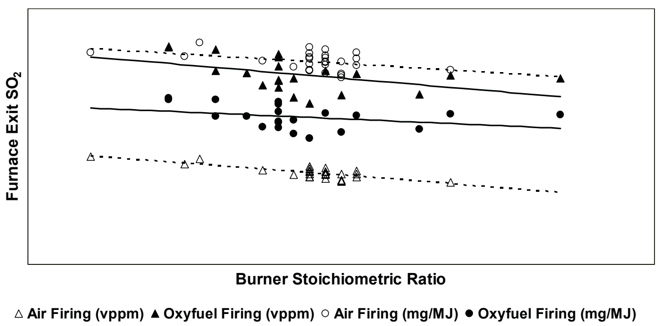

Figure 3: Effect of burner stoichiometric ratio on furnace exit SO_2

4.2. Effect of flue gas recycle ratio

The effect of flue gas recycle (FGR) ratio on furnace exit CIA is presented in Figure 4. Furnace exit CIA is increased at higher FGR ratio, due to lower flame temperatures and shorter residence time. The effect of FGR ratio on adiabatic flame temperature and residence time is presented in Figure 5.

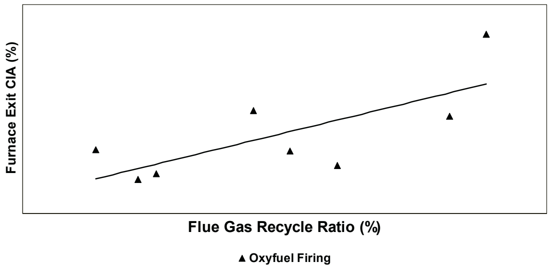

Figure 4: Effect of FGR ratio on furnace exit CIA

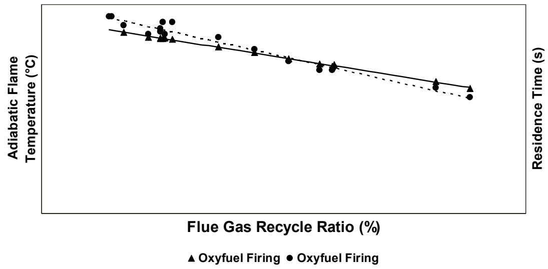

Figure 5: Effect of FGR ratio on adiabatic flame temperature and residence time

4.3. Effect of primary transport gas O_2 content

Oxyfuel combustion opens the possibility of supplying different amounts of O_2 injection to the both the primary transport gas and secondary flue gas recycle (FGR) streams. The effect of varying the O_2 content in the primary transport gas was investigated, and its impact on combustion performance is shown in Figures 6 and 7. Increasing the O_2 content in the primary transport gas leads to improved combustion; CO emissions are reduced, CIA is lower, and the flame monitor signal strength was increased.

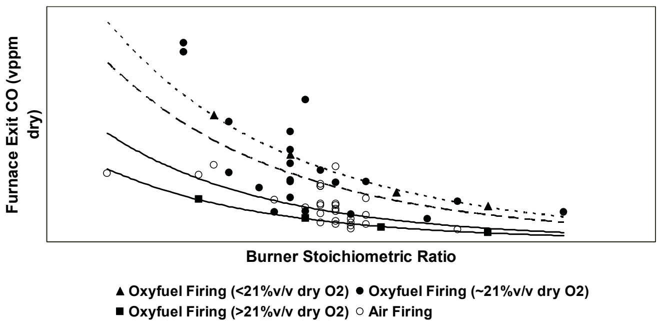

Figure 6: Effect of primary transport gas O_2 content on furnace exit CO

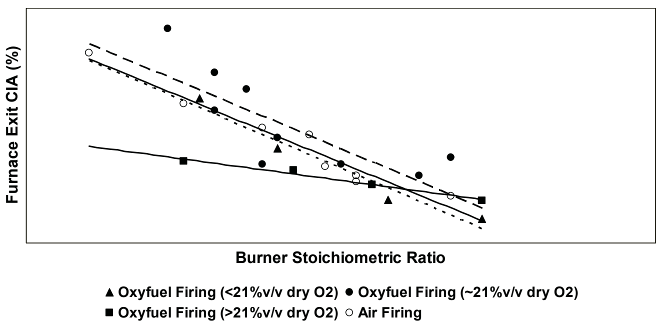

Figure 7: Effect of primary transport gas O_2 content on furnace exit CIA

4.4. Effect of selective catalytic reduction

Selective catalytic reduction (SCR) was principally utilized to reduce the NO concentration of the oxyfuel flue gas supplied to the sour compression rig, and the impact of the NO / SO_2 ratio on the CO_2 clean-up process is presented in [9]. Limited investigation of the effect of oxyfuel firing on SCR performance showed that the SCR was not adversely affected.

5. Demonstration of an oxyfuel combustion system

The project participants in the £7.4M UK Department for Business Enterprise & Regulatory Reform (BERR) Hydrogen Fuel Cells and Carbon Abatement Technologies (HFCCAT) Demonstration Programme collaborative project comprise: Doosan Babcock Energy Limited (Lead), Imperial College London and University of Nottingham. Scottish and Southern Energy plc, Air Products plc, ScottishPower Energy Wholesale, E.ON UK plc, EDF Energy plc, Drax Power Limited and DONG Energy A/S are sponsor participants, with Scottish and Southern Energy plc acting as prime sponsor.

The project aims to demonstrate an oxyfuel combustion system of a type and size (40MW$_t$) applicable to new build and retrofit advanced supercritical boiler plant. The stages of the project comprise development of a purpose designed oxyfuel demonstration facility (Doosan Babcock's 90MW$_t$ Multi-fuel Burner Test Facility) including detailed design and HAZOP study, installation and commissioning, design and manufacture of a first generation oxyfuel burner, and parametric testing of the 40MW$_t$ OxyCoal™ burner. The specific objectives for parametric testing are demonstration of safe operation and successful performance of the full-scale 40MW$_t$ OxyCoal™ burner firing at conditions pertinent to the application of an oxyfuel combustion process in a utility power generating plant, in terms of flame stability, NO_x, flame shape and heat transfer characteristics over a reasonable operational envelope with respect to start-up, turndown, shutdown and the transition between air and oxyfuel firing.

6. Multi-fuel burner test facility

The 90MW$_t$ Multi-fuel Burner Test Facility (MBTF) is designed primarily for the development of burners for fossil fuel firing applications and is one of the largest and most modern single burner test rigs in the world. The plant has been designed to enable burners to be developed, optimized and performance tested at full-scale prior to application in industrial plant.

The main component is a horizontal, water-jacketed test furnace that is partly lined with high temperature refractory. The furnace is 17 m long 5.5 m square. Observation ports are arranged along one side wall of the furnace on the burner centerline and flame probing access ports, are located on the opposite side wall. Photographic and video equipment is fitted for flame observation, monitoring and image recording. An adaptable windbox is fitted on one end of the furnace to accommodate single test burners with throat diameters up to a maximum of 2 m.

The facility is able to fire a wide variety of fuels; bituminous and low volatile coals, heavy and light fuel oil, Orimulsion™, natural gas. A 30 tonne storage silo, loss-in-weight feeder and pneumatic transport system is fitted for the supply of pulverized coal to the burner. The system has a maximum feed rate capability of 12 to 14 tonnes per hour depending on the bulk density of the material.

The draught plant consists of forced draught (FD), transport air, primary air (PA), core air and induced draught (ID) fans and blowers. Gas-fired airheaters are installed to raise fuel transport stream and combustion air temperatures to plant representative values. A multi-cyclone grit collection system is fitted for cleaning of flue gases prior to the ID fan.

A tri-drum boiler with superheater and economizer is installed to cool the flue gases from approximately 1200°C at the furnace exit to approximately 230°C

Two-stage combustion has been implemented on the MBTF by means of installing overfire air ports to the furnace sections to allow the testing of burners operating under staged combustion conditions. A laser-based technology to determine the temperature, O_2 and CO profiles in the flame has been installed.

For the conversion to oxyfuel, an oxygen storage facility comprising three liquid storage tanks each with a liquid oxygen capacity of approximately 50 tonnes, and eight ambient vaporizers to supply gaseous oxygen for injection into primary and secondary flue gas recycle (FGR) streams is being installed. The primary and secondary FGR streams will replace the primary air and main combustion air respectively, each having a dedicated fan. A transport FGR stream will replace the transport air stream. The transport and primary FGR stream will also have additional flue gas cooling systems fitted for drying and in-duct heating as a means to mitigate PF feeding problems with a high moisture flue gas. A proportion of the secondary FGR stream can be redirected to an overfire FGR system for two-stage combustion.

The programme envisages construction and installation to be complete by the early part of 2009, with burner testing being carried out during the remainder of 2009.

7. Conclusions

Parametric testing of the oxyfuel combustion process carried out on the 160kW$_t$ NO_x Reduction Test Facility (NRTF) has shown that oxyfuel firing NO and SO_2 emissions are lower on a heat input basis (mg/MJ) compared to air firing, carbon in ash (CIA) is higher at higher flue gas recycle (FGR) ratio, and combustion is improved at higher primary transport gas O_2 oxygen content, as indicated by lower CO emissions and CIA.

Considerable progress has been made in converting Doosan Babcock's 90MW$_t$ Multi-fuel Burner Test Facility (MBTF) to oxyfuel firing and in designing and manufacturing Doosan Babcock's 40MW$_t$ OxyCoal™ burner. Demonstration of the system is scheduled for 2009.

The current tasks complete the foundation for the development of an oxyfuel boiler reference design, demonstration plant installation and operation leading to commercialization of the technology.

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